REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-02-

0364

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
26-08-2002	Final Technical Report	15-05-1999 to 30-11-2001

4. TITLE AND SUBTITLE
Development of High Average Power Nonlinear Frequency Conversion Devices

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-99-1-0270

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Stanford, CA 94305-4088

8. PERFORMING ORGANIZATION REPORT NUMBER
SPO No. 20861

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR
801 North Randolph Street, Room 732
Arlington, VA 22203-1977

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S) GL No. 5763

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained herein are those of the author(s) and should not be construed as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

14. ABSTRACT
This program developed microstructured nonlinear optical materials and quasi-phasematched devices based on those materials. The two material systems investigated, periodically-poled ferroelectrics, especially lithium niobate (PPLN), and orientation-patterned GaAs (OP-GaAs), enable nonlinear interactions impossible in conventional nonlinear media. This work included the generation of the shortest blue light pulse then reported (5.4 fs), demonstration of orientation patterned GaAs (OP-GaAs), a mid-IR analog for PPLN operating to wavelengths > 12 μm with 10 times larger nonlinear figure of merit than PPLN, vapor transport synthesis of stoichiometric lithium tantalate (with no measurable room-temperature photorefractive damage), chirped-pulse parametric amplifiers generating millijoule ultrafast pulses in a simple single-pass configuration, guided-wave frequency mixers with efficiencies of 3000%/W, enabling demonstration of extreme phenomena such as 99% pump depleted SHG (with only 900 mW pump power), and optical parametric generators with 300 pJ thresholds. Significant projects seeded by the work in this program have been spun off as industry-supported projects, in particular optical signal processing devices for communications based on the waveguide mixers, and IRCM applications of the OP-GaAs.

15. SUBJECT TERMS
microstructured nonlinear optical materials, quasi-phasematched devices, periodically-poled lithium niobate, orientation-patterned GaAs, stoichiometric lithium tantalate, frequency conversion, non-linear optics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Martin M. Fejer
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code) (650) 725-2160

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

20021126 069

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Development of High Average Power Nonlinear Frequency Conversion Devices

Final Technical Report
for the period
15 March 1999 through 30 November 2001

Includes Interim Technical Reports
for the periods
15 March 1999 through 31 August 1999
1 September 1999 through 31 August 2000
1 September 2000 through 31 August 2001

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I. Introduction

This final technical report summarizes a three year program with AFOSR support under F49620-99-1-0270 on exploring microstructured nonlinear optical materials and quasi-phasematched (QPM) nonlinear devices based on them. The additional degrees of freedom afforded in such media, exemplified by periodically-poled lithium niobate (PPLN), and more recently, orientation-patterned GaAs (OP-GaAs), enable nonlinear interactions impossible in conventional nonlinear media. Among the results of this work were the generation of the shortest blue light pulse yet reported (5.4 fs), development of orientation patterned GaAs (OP-GaAs), a mid-IR analogue for PPLN operating to wavelengths > 12 μm with 10 times larger nonlinear figure of merit than PPLN, vapor transport synthesis of stoichiometric lithium tantalate (with no measurable room-temperature photorefractive damage), chirped pulse parametric amplifiers generating millijoule ultrafast pulses in a simple single-pass configuration, guided-wave frequency mixers with efficiencies of 3000%/W, enabling demonstration of extreme phenomena such as 99% pump depleted SHG (with only 900 mW pump power), and optical parametric generators with 300 pJ thresholds. Significant projects seeded by the work in this program have been spun off as industry-supported projects, in particular optical signal processing devices for communications based on the waveguide mixers, and IRCM applications of the OP-GaAs.

II. Technical Report

II.1 Materials

Our materials work over the past three years has made progress in four broad areas: orientation-patterned III-V semiconductors as analogues to PPLN for mid-IR QPM; synthesis and characterization of stoichiometric lithium niobate and tantalate with improved ferroelectric and optical properties compared to conventional congruently melting crystals; improved periodic-poling technology in conventional ferroelectrics; and waveguide fabrication in PPLN, based on substantially improved modeling capability, with order of magnitude increase in efficiency compared to prior work.

II.1.1 Orientation-Patterned GaAs

The III-V semiconductors are attractive materials for nonlinear optical frequency conversion, as they have large nonlinear susceptibilities (d_{14}(GaAs) = 5 x d_{33}(LiNbO$_3$)), broad IR transparency (to >12 μm in GaAs), and high thermal conductivities (~ 10 x LiNbO$_3$) that reduce the temperature rise resulting from absorbed optical power. Unfortunately, they are generally in the zincblende crystal structure, and as a cubic point group, lack birefringence of phasematching. They of course are not ferroelectric, so cannot be periodically poled. Since they have a $\bar{4}$ axis in the (100) direction, 90° twins around this axis invert the crystal structure, and so change the sign of the nonlinear susceptibility as is required for QPM. We have developed methods for lithographically patterning a substrate, to create a template that controls the orientation of subsequently grown films. This orientation-patterned GaAs (OP-GaAs) can be grown in thin-film form by MBE, or in thick films by hydride vapor-phase epitaxy (HVPE).[1]

Figure 1. A 0.5-mm-thick orientation-patterned GaAs. Domain width is 30 μm.

This material has exceptional properties for mid-IR nonlinear devices, simultaneously providing all the well-known advantages of QPM techniques while lifting the constraint limiting PPLN to < 4.5 μm operation due to multi-phonon absorption, and providing a figure of merit for focused nonlinear interactions 10 x larger than that of PPLN at the same wavelength, due to the larger nonlinear susceptibility of OP-GaAs (~ 100 pm/V)[2]
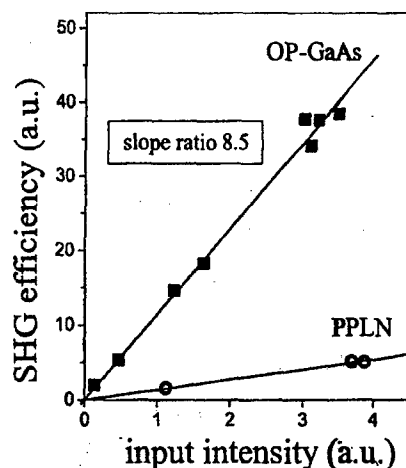
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Figure 2. SHG efficiency vs. input intensity for OP-GaAs and PPLN measured in side-by-side comparison in 4 μm fundamental wavelength. Inferred ratio of nonlinear susceptibilities is $d_{14}(GaAs)/d_{33}(LiNbO_3) = 6.2\pm0.6$ and nonlinear figure of merit for focused interactions FOM = d^2/n^2: FOM(GaAs)/FOM(LiNbO_3) = 10.

This material is truly a mid-IR analogue of PPLN, and will open that spectral range to the same range of techniques that have been so successfully applied at shorter wavelengths in PPLN. A number of other programs (see section IV) have picked up support of the further development of this material (and analogues like OP-GaP).

II.1.2 Stoichiometric Ferroelectrics

The engineerable nonlinear functionality available in periodically-poled ferroelectrics in general, and the large (4") low-cost substrates available in lithium niobate in particular, have opened many new areas of nonlinear optical physics and device applications. Despite these advantages, several persistent material issues limit the range of applicability of this material: its room-temperature photorefractive sensitivity forces operation at elevated temperatures; its electronic absorption edge limits operation in the near-UV; residual absorption limits high-average-power operation in the visible due to thermal focusing; and its high coercive field complicates poling plates thicker than ~ 1 mm. Several alternatives are possible; within the family of niobates and tantalates, in addition to magnesium doping as a means to reduce the photorefractive sensitivity. An area receiving considerable attention recently is the stoichiometric family of materials, where the [Li]/([Li]+[Nb]) – or [Li]/([Li]+[Ta]) in the case of lithium tantalate – ratio is made very close to 0.5, rather than the ~0.483 value typical of the "congruently melting" compositions that are the standard for commercial Czochralski-grown crystals. The vastly lower number of point defects in these stoichiometric crystals has a qualitative effect on many of their properties compared to congruent crystals. Two of the most important for QPM applications are the orders-of-magnitude larger photoconductivity (which proportionately reduces the photorefractive damage due to the Glass current) and the two-order-of-magnitude lower coercive field (as low as 100 V/mm in SLT) which facilitates the poling of thick plates.

Historically, use of stoichiometric crystals has been precluded by the near-impossibility of growing uniform crystals by conventional Czochralski techniques. We have developed a vapor-transport technique for converting conventional congruent composition crystals to (near) stoichiometric compositions.[3] This method, and a complex, but viable, melt growth method,[4] have generated interest in the stoichiometric materials. We have developed two measurement tools quite useful for characterizing the properties of stoichiometric ferroelectrics (as well as a variety of other optical materials). The photothermal common-path interferometer, an extremely sensitive tool for space-and-time-resolved measurement of the optical absorption (with ppm/cm sensitivity in ~ 1 s integration times), has proven invaluable for characterizing absorption effects in ferroelectrics (including complex phenomena like green-induced infrared absorption in PPLN and grey-tracking in KTP).[5] An apparatus for measuring transport properties (Glass currents and photoconductivity) of low-conductivity materials at high optical intensities was developed for characterization of the constitutive

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relations for properties that contribute to photorefractive damage, using transparent liquid contacts as a key innovation to avoid self-heating and the attendant large pyroelectric currents masking the currents of interest.
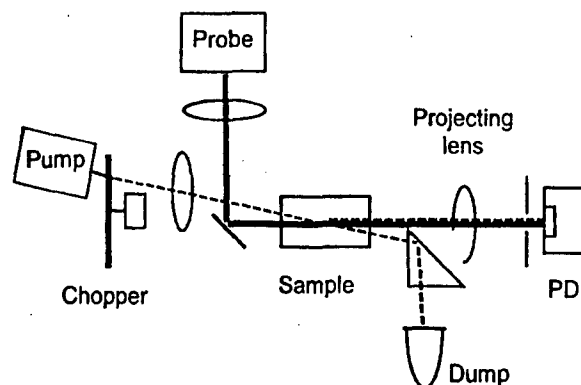

Figure 3(a). Photothermal common-path interferometer. Interferometric sensitivity combined with common-path stability enable measurement of absorption at the ppm level in millimeter volumes in tens of milliseconds.

We have applied these tools to the synthesis and characterization of stoichiometric LN and LT. Among the key findings are that coercive fields as low as 100 V/mm can be obtained in VTE SLT (lower than has been demonstrated by other methods) and that photoconductivities at least 3 orders of magnitude higher than CLN are available in SLT.[6] SLT with no measurable photorefractive damage at room temperature (consistent with the expectation from the transport measurements) has been observed. Key questions yet to be resolved are the elimination of an absorption tail extending into the visible in SLT, and developing an understanding of the marked differences between SLT and SLN (which shows non-negligible photorefractive damage, despite its high photoconductivity).
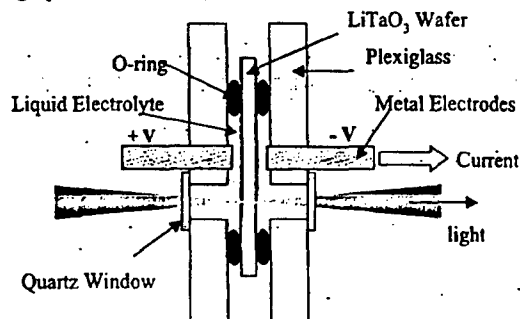
Figure 3(b). Apparatus for measurement of transport properties at high optical intensities. Transparent electrolyte contact enables probing photo-induced currents at high intensities without interference from pyroelectric currents due to sample heating.

II.1.3 Periodic Poling Technology

The technology of periodic poling has been under continuous development in our laboratory for over one decade. Fabrication of gratings for NIR and MIR devices has been a standard process for some time, so that recent work focused on extending the technology with precise placement and phasing of small gratings for integrated nonlinear optical devices, such as the OF balanced mixer, and arrays of small domains to emulate nearly arbitrary poling distributions for "nonlinear physical optics" devices. Modifications to the standard process, including an improved poling fixture, a modified waveform for the poling field, and the use of fine alignment markers have enabled routine fabrication of structures like those shown in Figure 4 and Figure 5.
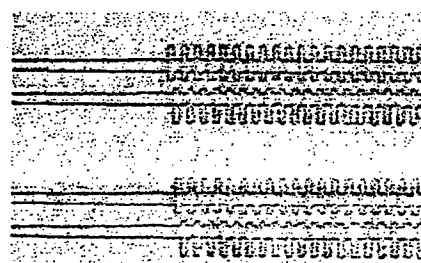
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Figure 4. Two QPM gratings, aligned with adjacent waveguides, showing precise control over domain placement and phasing.
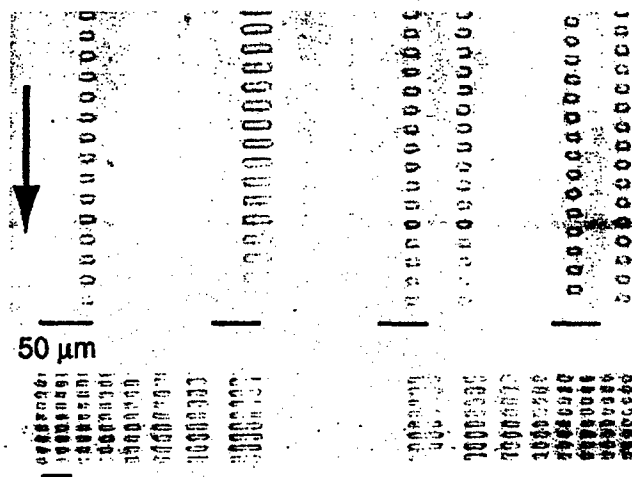

50 μm

Figure 5. Single and double slit diffraction devices, and a Fresnel lens structure for QPM physical optics demonstrations. The arrow indicates propagation direction; bar represents 50-μm. Domains are revealed by etching. Use of these structures for nonlinear physical optics is discussed in section II.2.3.

II.1.4 Waveguide Fabrication

Highly efficient waveguides are applicable both to optical signal processing devices and to coherent optical sources. Fabrication techniques for nonlinear waveguide devices have thus been a focus of our efforts over the past three years; nearly an order of magnitude increase in the efficiency has been obtained over this time. The conversion efficiency in a nonlinear waveguide depends on the modal overlap, the modal confinement, and the length over which the interaction can usefully be phasematched. Control over the transverse shape of the refractive index profile and its axial homogeneity are the keys to improving these quantities. As the level of performance we demand increases, so must the precision of the modeling of the waveguide fabrication process.

The basic process we use for waveguide fabrication is annealed proton exchange (APE). This involves an initial ion exchange process, where the PPLN substrate is immersed in an acid bath, such that protons (H^+ ions) replace lithium (Li^+ ions) in a step-like distribution at the surface. Subsequent annealing allows for engineering the index profile to support a desired number of modes at the wavelengths of interest. Modeling is complicated by concentration-dependent proton diffusion and material dispersion. Using careful measurements of the propagation constants of planar waveguides fabricated under a range of conditions, we have characterized the concentration-dependent diffusivity of protons in lithium niobate as well as the dependence of the refractive index of protonated lithium niobate on wavelength and proton concentration. A numerical model for the diffusion process has been developed using the diffusivity data. Coupled with the dispersion data, this model allows for accurate prediction of waveguide refractive index profiles resulting from given processing conditions. These refractive index profiles, in turn, completely determine the modal properties of the waveguides, so that we can now accurately predict both the linear and nonlinear performance of waveguide devices based on APE waveguides. We first developed such a model in the early 1990's; the refinements made in the last year have been required to enable accurate design of more complex structures operating over a broader range of wavelengths, particularly important as we are integrating multiple devices on a single chip.

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A limitation on the efficiency of conventional APE waveguides is the inherently asymmetric refractive index profile, which leads to spatial modes that are similarly asymmetric in depth. The spatial overlap of modes at highly disparate wavelengths is then sub-optimal, as the peaks of the modes do not coincide in this dimension. A key step towards increasing the modal overlap was the development of buried waveguides, in which the symmetric refractive index profile leads to modes whose peaks are nearly coincident in depth, so that the modal overlap is improved. Buried waveguides are fabricated by immersing the APE waveguides in a lithium-rich melt, such that protons diffuse out of the substrate and are replaced by lithium ions, producing a symmetric index profile in depth. The normalized mixing efficiency of these buried waveguides is increased approximately three-fold over conventional APE designs[7]. Figure 6 shows the refractive index profile and nearly round mode obtained in such a buried waveguide.

The inevitable small deviations from the ideal waveguide geometry that result from imperfect fabrication conditions can limit the useful length of nonlinear devices by causing randomly accumulating phase mismatch along the length of the device. Given the quadratic scaling of the efficiency with the length of the device, a key step in fabricating ultra-efficient devices is the use of noncritical designs, with no first order dependence on small deviations from the nominal geometry. Through the use of the precise waveguide model, and some empirical refinement, we have developed noncritical designs for both conventional APE and buried APE waveguides, allowing nearly ideal tuning behavior over lengths as large as 6 cm (Figure 7).
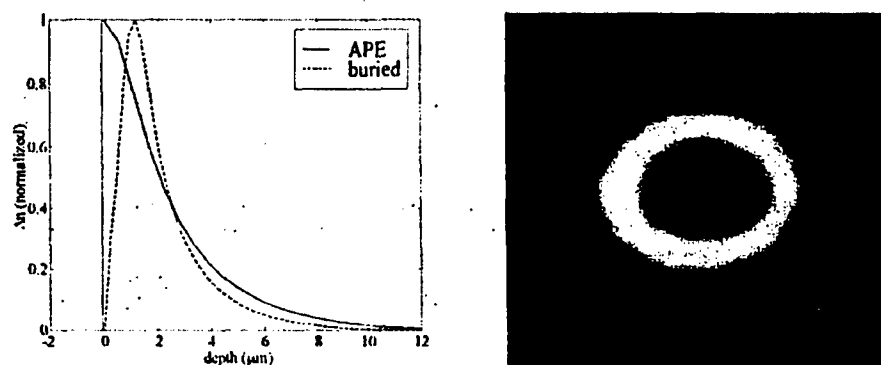

Figure 6. Comparison of refractive index profiles for APE and buried waveguides, and measured nearly-round mode observed in buried waveguide.
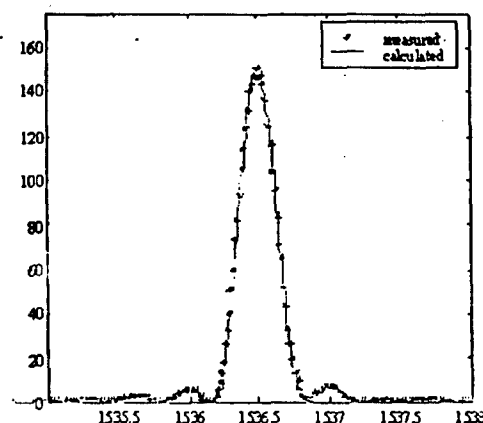

Figure 7. SHG tuning curve for a 3-cm-long buried APE waveguide, showing nearly ideal homogeneity, and peak normalized efficiency of 150%/W-cm^2 at 1.5-μm wavelengths.

II.2 Devices

Work over the past three years has progressed in ultrafast optical devices, novel amplification methods, and waveguide interactions (especially multi-function integrated devices). Quite recently, we have seen exciting results in two new areas which are termed "nonlinear physical optics" (manipulating an optical wavefront in a fashion similar to conventional physical optics devices, but implemented with patterning of the nonlinear rather than the linear material properties), and "extreme" nonlinear optics (pushing nonlinear interactions into regimes not previously explored, e.g. SHG with 99% pump depletion).

II.2.1 Ultrafast Optical Devices

We have devoted considerable effort in recent years to engineering the temporal response of nonlinear devices via longitudinally aperiodic QPM gratings. We found that it was possible to create nonlinear analogues to conventional optical devices like spectral filters and dispersive delay lines, but with interesting and useful differences, such as optical filters able to generate outputs with higher spectral intensity than their inputs,[8] and delay lines with nearly arbitrary dispersion easily patterned with conventional lithographic methods.[9,10] These tools were applied to devices like monolithic pulse compressors for chirped-pulse fiber amplifiers,[11] generation of record short (5.4 fs) blue light pulses,[12] "arbitrary" pulse generators,[13] and perfectly synchronized two-color pulse generation.[8]

These devices can in general be viewed as (and designed in analogy to) spectral filters, whose filter function is proportional to the spatial Fourier transform of the nonlinear coefficient in the structure. Thus, nearly arbitrary spectral (and therefore temporal) filtering is readily designed through an appropriate domain pattern.
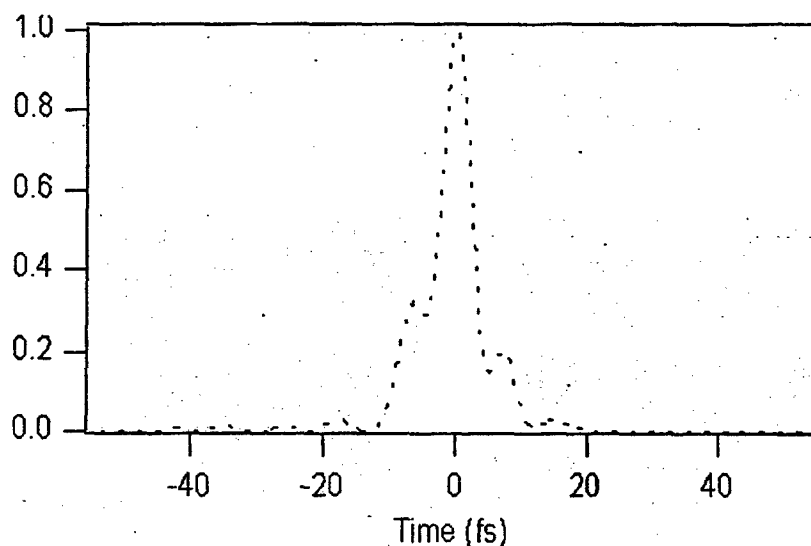

Figure 8. 400 nm blue light pulse generated in nonlinearly chirped PPLT crystal. 5.4 fs duration, shortest reported to that time, was enabled by the correction of "all" orders of dispersion through the design of the nonlinearly chirped QPM grating.

II.2.2 Waveguide Interactions

Work on waveguide interactions over the previous three years has emphasized devices for optical signal processing in fiber optic communications systems, and hence operation at 1.5 μm. Significant progress has been made in the fabrication of these devices (section II.1.4), enabling applications like wavelength conversion at speeds up to 160 Gbit/s,[14] spectral inversion (phase conjugation) for dispersion compensation,[15] gated

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mixing at speeds up to 100 Gbit/s for optical time division multiplexing[16] and picosecond optical sampling.[17] Industrial interest in this these applications is manifested in several commercialization efforts.
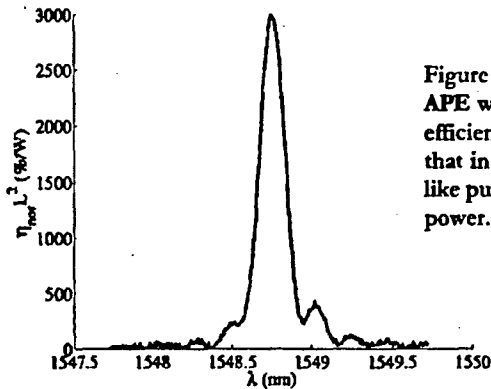

Figure 9. SHG tuning curve for a 6-cm-long buried APE waveguide, showing good homogeneity, and peak efficiency of 3000%/W at 1.5-µm wavelengths. Note that in such strongly nonlinear waveguides phenomena like pump depletion are manifested at 10's of mW pump power.

The technology developed for these communications applications can also be used to further the development of ultrafast and coherent sources in other parts of the spectrum than the 1.5–µm band (in some sense going full circle back to the early developments in QPM waveguide nonlinear devices driven by the demand for a compact blue light source). The high mixing efficiencies (3000%/W demonstrated, ~6000%/W anticipated) and the nature of modal rather than free-space interactions enable pushing the extremes of nonlinear optical physics, especially when used in concert with the engineered spectral response (section II.2.1) in chirped QPM gratings.

As the performance of single devices on a chip becomes ever better, it becomes increasingly interesting to explore multi-function devices in which more than one function is integrated on a single chip. The extra degrees of freedom available in such structures enable greater control over, for example, ultrafast devices with integrated seed pulse and time delay generation. We have developed a suite of functional components compatible with single-chip APE integration, including directional couplers, Y-junctions, and small-radius bends. These integrable components will be key building block for the next generation devices.
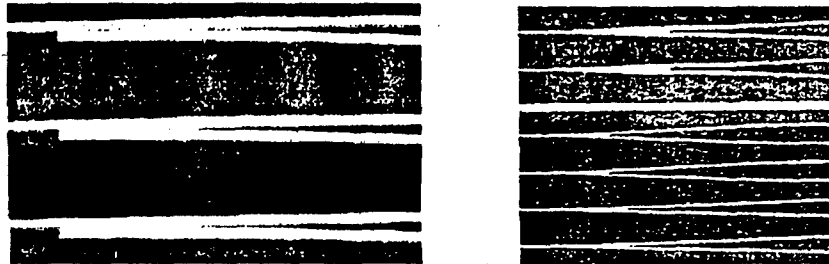

Figure 10. Directional couplers and Y-junctions fabricated in APE waveguides for integrated QPM devices.

Several new concepts have emerged in the course of this work, including the optical-frequency balanced mixer,[18] and quasi-group-velocity matching.[19] The latter, especially, can have an impact on ultrafast optics through its lifting of the limitations imposed by group-velocity walkoff on the interaction lengths available

II.2.3 New Directions

We have quite recently had some exciting results in two areas, "nonlinear physical optics", nonlinear analogs of conventional physical optics devices like lenses, gratings, and beamsplitters, and "extreme" nonlinear optics, devices pushing performance boundaries, such as 99% pump depletion in SHG, and CW parametric gains exceeding 6 dB. These topics are discussed in the next two sections, respectively.

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II.2.3.1 Nonlinear Physical Optics

Given the close analogy between space and time in optical physics, it is to be expected that interactions comparably interesting to those involving manipulation of ultrafast pulses in the time domain should be possible in the space domain in media patterned in the direction transverse to the beam propagation. Much more limited effort has been devoted to engineering the spatial response of nonlinear devices via transversely varying QPM gratings.[20],[21] We have recently begun to explore the possibilities of fairly general transverse patterning of QPM gratings; there has emerged a rather rich collection of phenomena, with analogues of many conventional physical-optics devices possible.

These nonlinear physical optics devices are based on variations in QPM-grating amplitude and phase in the direction transverse to the beam propagation. Consider SHG as a simple example, though many of the more interesting phenomena will involve the three-wave interactions, DFG or SFG. The simplest to visualize is a strip of periodically-poled material surrounded by uniformly poled crystal. This structure generates at the output of the crystal a SH field that is "top-hat" of the same width as the poled strip, i.e. it is the same field as would have been passed by a hard edged slit in an opaque screen. Multiple slits obviously can be engineered simply by patterning several parallel regions of periodic-poling. It is also easy to add an arbitrary phase to the output of the various slits by shifting the phase of the underlying QPM gratings. Several such structures are shown in Figure 4 and Figure 5.

It is clear that the performance of these devices relies on the methods for precision domain placement and phasing described in section II.1.3. With these tools, substantially more sophisticated structures than a simple slit are possible, for example a curved QPM grating would impose a radially varying phase on the generated beam, focusing it much as would a conventional lens. Shown in Figure 11 is such a QPM "lens", and in Figure 12a the spot size vs. distance of a beam exiting several such devices with different focal lengths (grating curvatures). It can be seen that the output beam behaves as an almost perfect diffraction limited Gaussian beam, and the waist is the one predicted by simple lens-law transformations of the input beam. An interesting feature of these QPM lenses is that they are converging in one direction and diverging in the other, in marked contrast to conventional lenses. (Figure 12b).
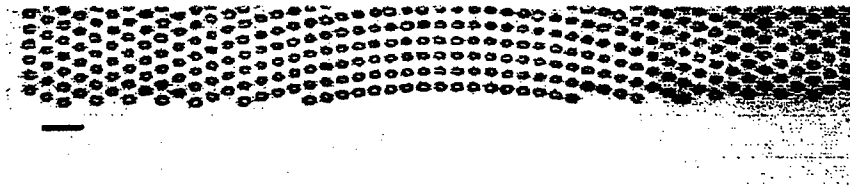

Figure 11. QPM lens, with focal length determined by curvature of the grating. The structure is analogous to a Fresnel lens, since the curved domains have been flattened into a series of convenient thickness sections, with phase resets by an integer number of 2π. Fabrication of the lens required use of the improved poling techniques described in section II.1.3.
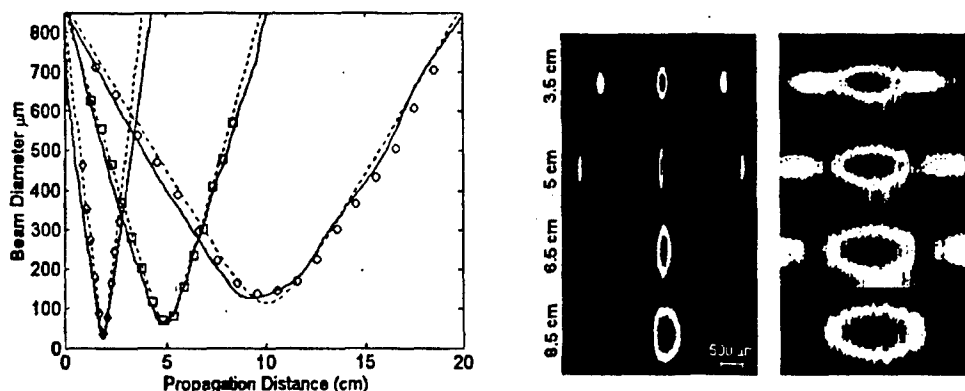
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Figure 12. (a) Beam waist vs. position after the lens. Note the near-diffraction limited focusing. (b) Cross-section of the SHG beam generated by fundamental beams passing forward and backward through the same lens. Note that in one direction the lens is converging and in the other diverging, in contrast to conventional lenses.

Other possible structures immediately suggest themselves. For example, two superposed gratings at a small angle to each other would serve as beamsplitter or combiner, pairs of wedge-shaped gratings phase-shifted 180° would act as a prism, etc. This work is in its early stages; the implications for applications are just emerging. Among the clear possibilities are their use in conjunction with DFG and SFG to impose the time structure of one beam on the other, e.g. to create time gated lensing or beam deflection. In single-beam interactions, strong nonlinear radially-varying phase shifts would have clear use as artificial Kerr lens materials for mode-locking (and in two-beam form offer optical synchronization as well). The use of QPM lenses as devices to help stabilize pulsed OPOs through apodizing amplitude and phase of the gain also seems a significant application. It is not clear what effect the non-reciprocal nature of the QPM lens would have on its use as an intracavity element in a standing-wave cavity; the ability to independently manipulate the forward and backward beams in the cavity seems possible, a unique capability previously unavailable in simple cavities. Another fruitful direction to explore is the quantum optical properties of devices like the nonlinear beamsplitter/combiner.

II.2.3.2   Extreme Nonlinear Optics

Highly nonlinear waveguides
The extremely high efficiency of QPM waveguide devices makes it possible to explore regimes of nonlinear optical interaction that have previously been inaccessible. An example of recent work in this direction was the demonstration of 99% pump depletion in traveling wave SHG, an order of magnitude more than has been demonstrated in bulk interactions (Figure 13a). Only 900 mW of peak pump power was required to reach this level in a device with normalized efficiency of 1400%/W. This performance is possible because the modes interact as entities, avoiding the transverse variations in efficiency that limit interactions between Gaussian beams. The relatively low pump powers required (due to the high efficiency of the waveguide) can be sliced out of a CW beam leading to simple time structure. The uniformity of the device was sufficient that phase mismatch due to random inhomogeneities in the structure did not accumulate to the point of causing significant back conversion. Figure 13b shows a wavelength tuning curve for SHG in the highly depleted regime. The narrowing of the width of the main lobe and the rise of the sidelobes (characteristic of the Jacobi elliptic function that forms the solution to the SHG equations in this limit) are clearly observed here.
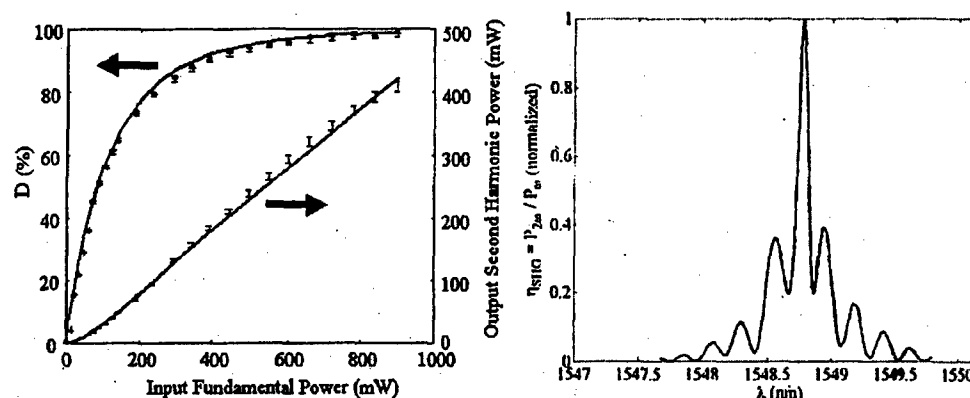
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Figure 13. (a) Pump depletion vs. input power, showing 99% depletion obtained at 900 mW pump power. (b) Second harmonic output vs. pump wavelength, showing narrowing of central peak and increasing sidelobes predicted by Bloembergen's classic analysis.[22]

Key to obtaining devices with these characteristics were the waveguide fabrication techniques discussed in section II.1.4. Note that with the current 3000%/W waveguides (section II.2.2), the power required to reach this limit would be reduced another factor of 2, to ~450 mW. The parametric gain from the SH generated in this device was so large (> 14 dB at maximum depletion) that it was necessary to wedge the end faces of the sample to avoid parametric oscillation.

Quasi-Group-Velocity Matching

A limitation on nonlinear interactions between ultrafast pulses is the difference in group velocities between the interacting fields. This group velocity mismatch (GVM) leads to temporal walkoff, limiting the useful interaction length to the distance over which the pulse envelopes walk off each other. For PPLN in the vicinity of 1.5 μm fundamental wavelength, the walkoff length for a 1 ps pulse is ~ 3 mm. Since the efficiency scales with the square of the interaction length, this limitation on the efficiency is significant – the high efficiency of ultrafast QPM devices stems from the large nonlinear coefficient compensating for this walkoff effect. Means to ameliorate the walkoff effect would enable a further quadratic increase in efficiency, with potential for operation at the femtojoule level.

Directional coupler separates long and short wavelengths

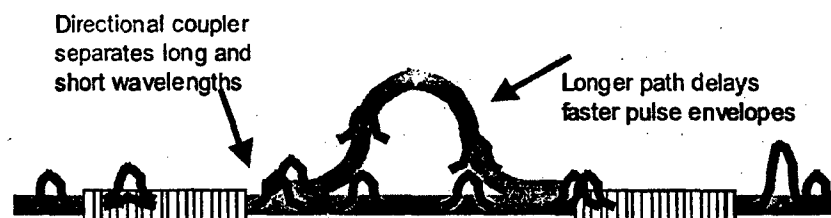Longer path delays faster pulse envelopes

Figure 14. Quasi-group-velocity matching (QGVM). The walkoff of the envelopes of the interacting waves is reset by inserting a periodic time delay. The efficiency increases as N^2 for N such sections in the device.

With this motivation, we have been exploring a concept we have called "quasi-group-velocity matching" (QGVM) in which a periodic time delay is inserted for one of the interacting waves to reset its envelope compared to that of the slower wave, e.g. the 1.5 μm signal interacting with a 780 nm pump. This concept is illustrated in Figure 14. The device is very much analogous to the use of periodic sign changes in $\chi^{(2)}$ to compensate for phase-velocity mismatch, hence the term QGVM. The waveguide components described in section II.2.2 enable the fabrication of the required structures; a first pass at this device showed promising results. We anticipate that successful operation will occur after one or two more design iterations.

Individually and especially used together, these two tools, highly nonlinear waveguides and quasi-group-velocity matching, open regimes of nonlinear drive and control over time domain phenomena unprecedented in nonlinear optical technology. In addition, they will also enable exploration of previously inaccessible regimes in,

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for example, high gain CW parametric amplifiers, ultrafast interactions with femtojoule pulse energies, multiple cascaded nonlinear interactions, novel mode-locking and pulse synchronization schemes, and quasi-CW OPG. Investigating the operation of such devices, and their utility in fields like quantum optics, optical signal processing, precision measurements, as well as in coherent sources will form an important part of future proposed work.

III. Summary and Future Directions

The program described here has been successful in extending QPM technology and developing new devices, and this argues strongly for continued research in related directions such as nonlinear physical optics, analogues of conventional physical optics devices (lenses, gratings, beamsplitters, ...) implemented in nonlinear form, extreme nonlinear devices pushing the envelope of nonlinear optical physics in highly efficient, single-spatial-mode devices, and novel coherent sources based on engineered optical parametric amplification, as well as capitalizing on the progress in microstructured nonlinear materials and device topologies to advance the state of the art in coherent optical sources.

A number of programs have grown out of the AFOSR-supported work described here. These include the Air Force CARMA programs at BAE and Northrup/Grumman/Litton, which are developing mid-IR sources based on OP-GaAs for IRCM, a MURI on Chalcopyrites and Related Materials (a major portion of which is supporting OPGaAs research), a consortium of four companies supporting the research on telecom signal processing components, and SPRC, the Stanford Photonics Research Center. It is worth noting that with the exception of the MURI, these are industrial programs, which testifies to the rapidity with which some of the apparently esoteric results of the research here has found its way into useful applications. It is also worth noting that many of the results developed are of direct relevance to DoD goals in general, and Air Force goals in particular. We anticipate that our future results will again push the envelope of what is currently practical and will again follow a similarly successfully trajectory.

IV. Program Participants

Martin M. Fejer	Co-Principal Investigator
Robert L. Byer	Co-Principal Investigator
Roger Route	Senior Research Associate
Alex Alexandrovski	Research Scientist
Frederic Bourgeois	Post-Doctoral Associate
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Loren Eyres	Graduate Student Research Assistant (Ph.D. – 2002)
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Krishnan Parameswaran	Graduate Student Research Assistant (Ph.D. – 2002)
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Andrew Schober	Graduate Student Research Assistant
William Tulloch	Graduate Student Research Assistant
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V. Publications Supported Directly

1. G. Imeshev, M. A. Arbore, S. Kasriel, and M. M. Fejer, "Pulse Shaping and Compression by Second-Harmonic Generation with Quasi-Phase-Matching Gratings in the Presence of Arbitrary Dispersion," J. Opt. Soc. Am. **B-17**, 1420-1437 (August 2000).

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VI. Publications Supported through Facilities

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